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Author(s):	Rauch, Eric Benton
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Signatures of Extended Storage of Used Nuclear Fuel in Casks

Eric Rauch

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HOWDY

- **B.S. Nuclear Engineering, Texas A&M University, 2006**
- **M.S. Nuclear Engineering, Texas A&M University, 2009**
  - Thesis – “Development of a Safeguards Approach for a Small Graphite Moderated Reactor and Associated Fuel Cycle Facilities”
- **Staff Member, Los Alamos National Laboratory, 2009-Present**
- **Primary focus on Radiation Detector Design and Optimization with Safeguards Applications**
  - Transverse Uranium Neutron Detector
  - Next Generation Safeguards Initiative
  - Unique Cask Identification
- **Married, Almost 4 year old triplets + 7 month old**

Agenda

- Abstract
- Purpose
- Proposed Signature
- CASTOR V/21 Model
- TN-32 Model
- HI-STORM 100S with MPC-32 Canister
- Tests with real data from real casks
- Final Thoughts

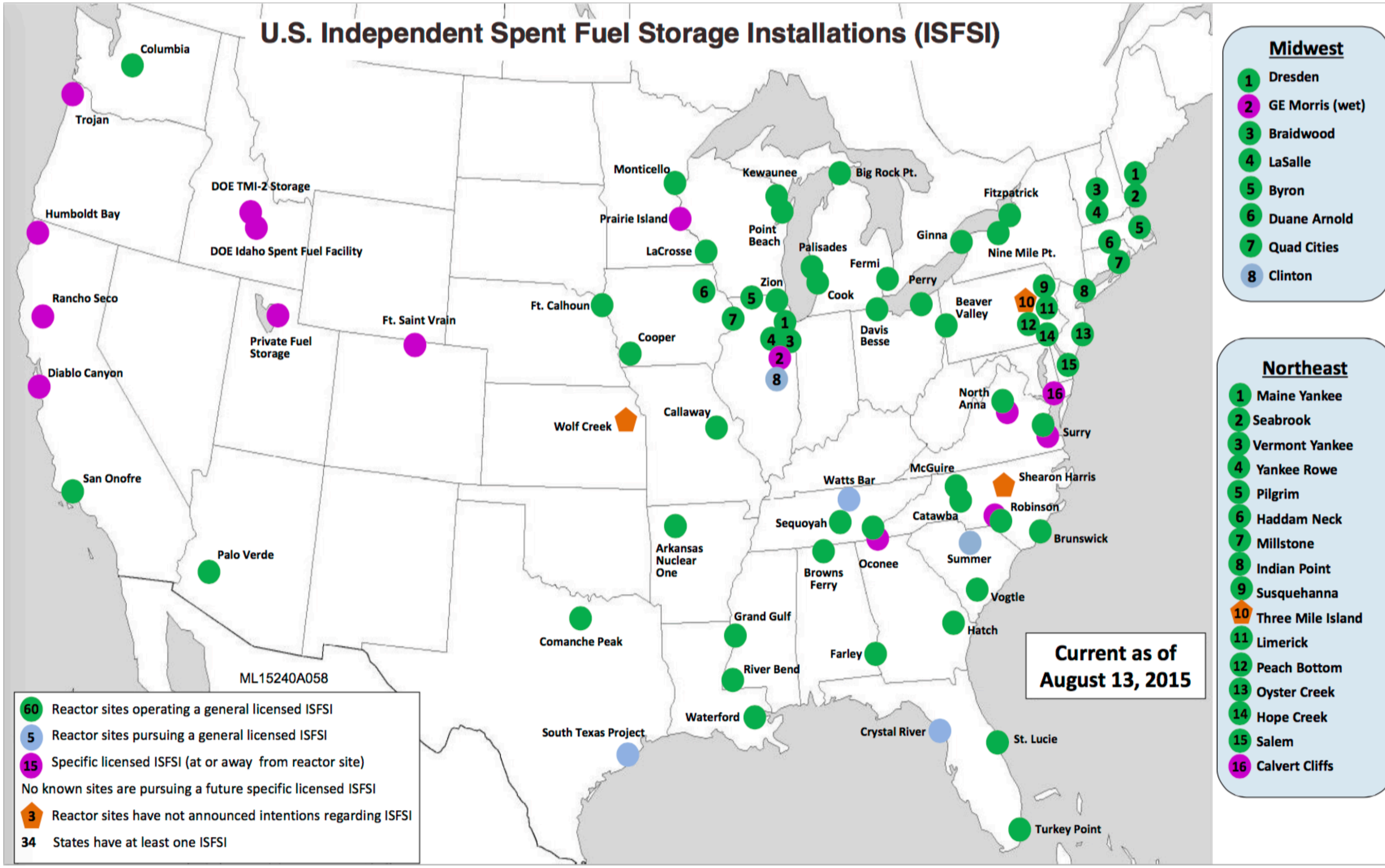
Abstract

As the amount of used nuclear fuel continues to grow, more and more used nuclear fuel will be transferred to storage casks. A consolidated storage facility is currently in the planning stages for storing these casks, where at least 10,000 MTHM of fuel will be stored. This site will have potentially thousands of casks once it is operational. A facility this large presents new safeguards and nuclear material accounting concerns.

A new signature based on the distribution of neutron sources and multiplication within casks was part of the Department of Energy Office of Nuclear Energy’s Material Protection, Account and Control Technologies (MPACT) campaign. Under this project we looked at fingerprinting each casks neutron signature. Each cask has a unique set of fuel, with a unique spread of initial enrichment, burnup, cooling time, and power history. The unique set of fuel creates a unique signature of neutron intensity based on the arrangement of the assemblies.

The unique arrangement of neutron sources and multiplication produces a reliable and unique identification of the cask that has been shown to be relatively constant over long time periods. The work presented here could be used to restore from a loss of continuity of knowledge at the storage site. This presentation will show the steps used to simulate and form this signature from the start of the effort through its conclusion in September 2016.

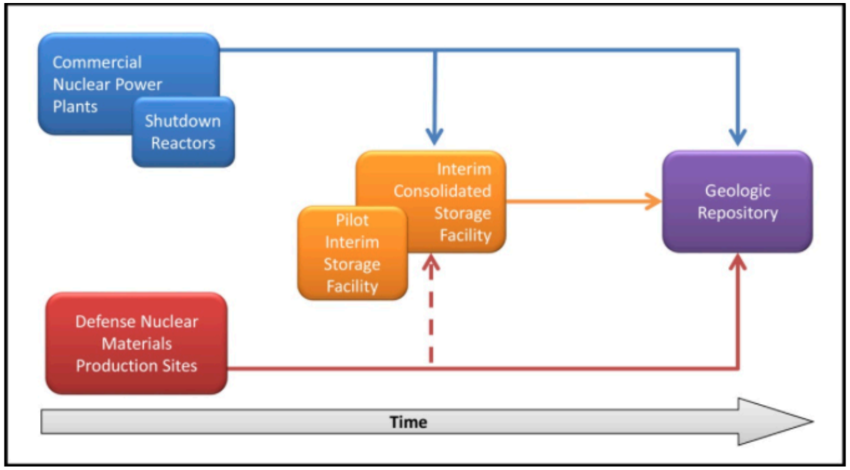
Current Used Fuel Storage Strategy



Source: http://pbadupws.nrc.gov/docs/ML1524/ML15240A058.pdf

Moving From Individual to Consolidated

- **As work continues on permanent geologic storage, an interim storage facility is being designed**
- **It is conceivable that multiple interim sites will be constructed, and used fuel could be stored for decades at these sites**



From the Strategy For The Management And Disposal Of Used Nuclear Fuel And High-level Radioactive Waste Jan 2013 Report

Interim Consolidated Storage Facility

- Receive fuel from multiple sites, weekly shipping
- Long term storage in casks
- Fuel stored for decades on site
- Need a way to restore continuity of knowledge if lost
- Need a method that will indicate state of fuel inside the cask

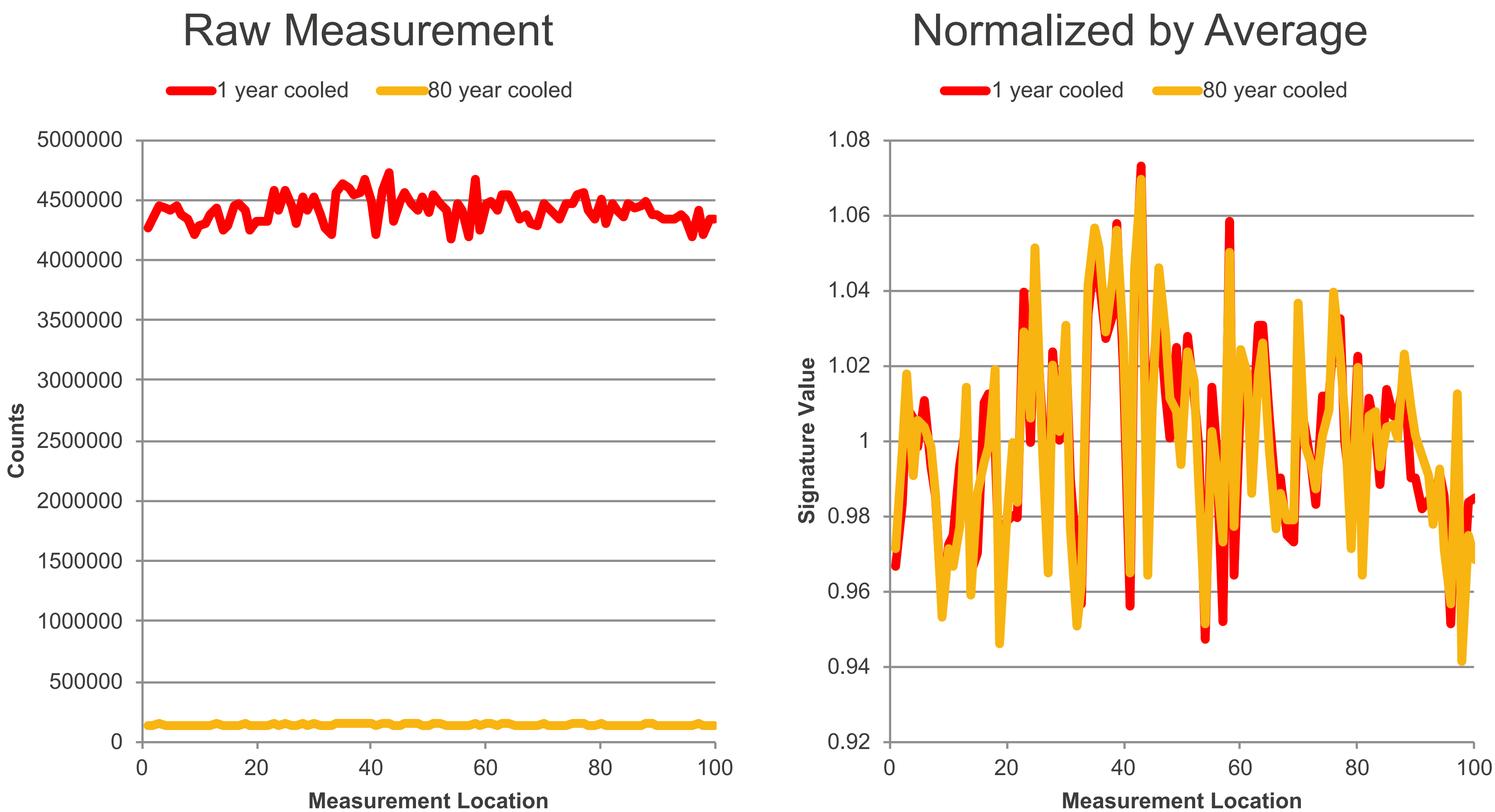
Potential Signatures

- **Neutron**
  - Provides information from whole cask
  - Burnable poisons are built in to some designs
- **Gamma**
  - Isotope Identification much easier
  - Can only provide information from the outer assemblies
- **Thermal**
  - Can be very accurate with Plutonium mass
  - Less accurate outside of calorimetry
- **Combination**
  - Increases complexity

Proposed Signature

- Used nuclear fuel is identifiable by its radiation emission, both gamma and neutron.
- Used nuclear fuel contains most of the fissile material of fresh fuel.
- Neutron emission from fission products, multiplication from remaining fissile material, unique distribution of both in each cask produces a unique neutron signature.
- The neutron signature around the outside of the cask will vary due to specific arrangement of fissile material and neutron sources of a specific cask.
- For these simulations, 100 points around the cask were sampled to generate a profile at the axial mid-point of the fuel

Taking a Measurement



Proposed Unique Signature

- Take count of neutrons being emitted from cask at more than 1 location around the cask (50-100 locations)
- Divide each count by the average of all counts
- That value is the fingerprint value for each location
- The Unique Signature is the collection of fingerprint values

Matching Signatures

- Normalized Signatures should be constant over time
- With 2 signatures from the same cask, a ratio of the points that make up the signatures should all approach 1
- Significant deviation from a ratio of 1 indicates something has changed in the distribution of sources and fissile material
- Only two things can make that happen, changes within the fuel content or misidentification of a cask
- Matching signatures should only have a small number of ratios that do not approach 1

Example

Present Day

Cell	ftc901	ftc902	ftc903	ftc904	ftc905
201	0.884548	0.835042	0.763931	0.699625	0.927967
202	1.07409	1.043721	0.867333	0.81919	1.186605
203	1.026387	1.040131	0.950534	0.873292	1.062191
204	1.188567	1.123793	1.054175	1.009176	1.236628
205	0.923331	0.849819	0.7975	0.713087	0.926715
206	1.028171	1.006883	0.970193	0.865605	0.967905
207	1.097575	1.179101	1.051269	1.011554	1.056284
208	1.002986	1.159869	0.977997	0.910055	0.944972
209	1.09638	1.210749	1.005695	0.940112	0.994656
210	1.066123	1.205031	1.091817	1.054766	1.030288

100 Years From now

Cell	ftc901 decayed	ftc902 decayed	ftc903 decayed	ftc904 decayed	ftc905 decayed
201	0.897353	0.836949	0.789733	0.692214	0.944112
202	1.079095	1.043142	0.884016	0.822175	1.180405
203	1.058843	1.052898	0.964998	0.839931	1.078843
204	1.199351	1.138983	1.080828	0.990391	1.269484
205	0.912433	0.843377	0.788991	0.689122	0.938768
206	1.043891	1.01354	0.976548	0.866698	0.99442
207	1.063737	1.198932	1.045523	1.016346	1.076974
208	0.994923	1.159735	0.986313	0.915362	0.94033
209	1.089526	1.226178	1.014467	0.940453	0.973417
210	1.054643	1.217528	1.092983	1.066082	1.052753

Future/Present

Cell	ftc901 ratio	ftc902 ratio	ftc903 ratio	ftc904 ratio	ftc905 ratio
201	1.014476	1.002283	1.033775	0.989407	1.017398
202	1.00466	0.999446	1.019236	1.003645	0.994775
203	1.031621	1.012274	1.015217	0.961799	1.015677
204	1.009072	1.013517	1.025283	0.981386	1.026569
205	0.988197	0.99242	0.98933	0.966393	1.013006
206	1.015289	1.006612	1.00655	1.001262	1.027393
207	0.96917	1.016819	0.994535	1.004737	1.019588
208	0.991961	0.999884	1.008503	1.005832	0.995088
209	0.993748	1.012743	1.008722	1.000363	0.978647
210	0.989232	1.01037	1.001068	1.010728	1.021805

Compared to FTC901

Cell	ftc901/ftc901	ftc901/ftc902	ftc901/ftc903	ftc901/ftc904	ftc901/ftc905
201	1.014476	1.07462	1.174652	1.28262	0.967009
202	1.00466	1.033893	1.244154	1.317272	0.909397
203	1.031621	1.01799	1.113945	1.212473	0.996848
204	1.009072	1.067234	1.137715	1.188445	0.969856
205	0.988197	1.073679	1.144116	1.279554	0.984588
206	1.015289	1.036755	1.075961	1.205966	1.078505
207	0.96917	0.902159	1.01186	1.051586	1.007056
208	0.991961	0.857789	1.017306	1.093256	1.05286
209	0.993748	0.899877	1.083356	1.158932	1.095379
210	0.989232	0.8752	0.965952	0.999883	1.023639

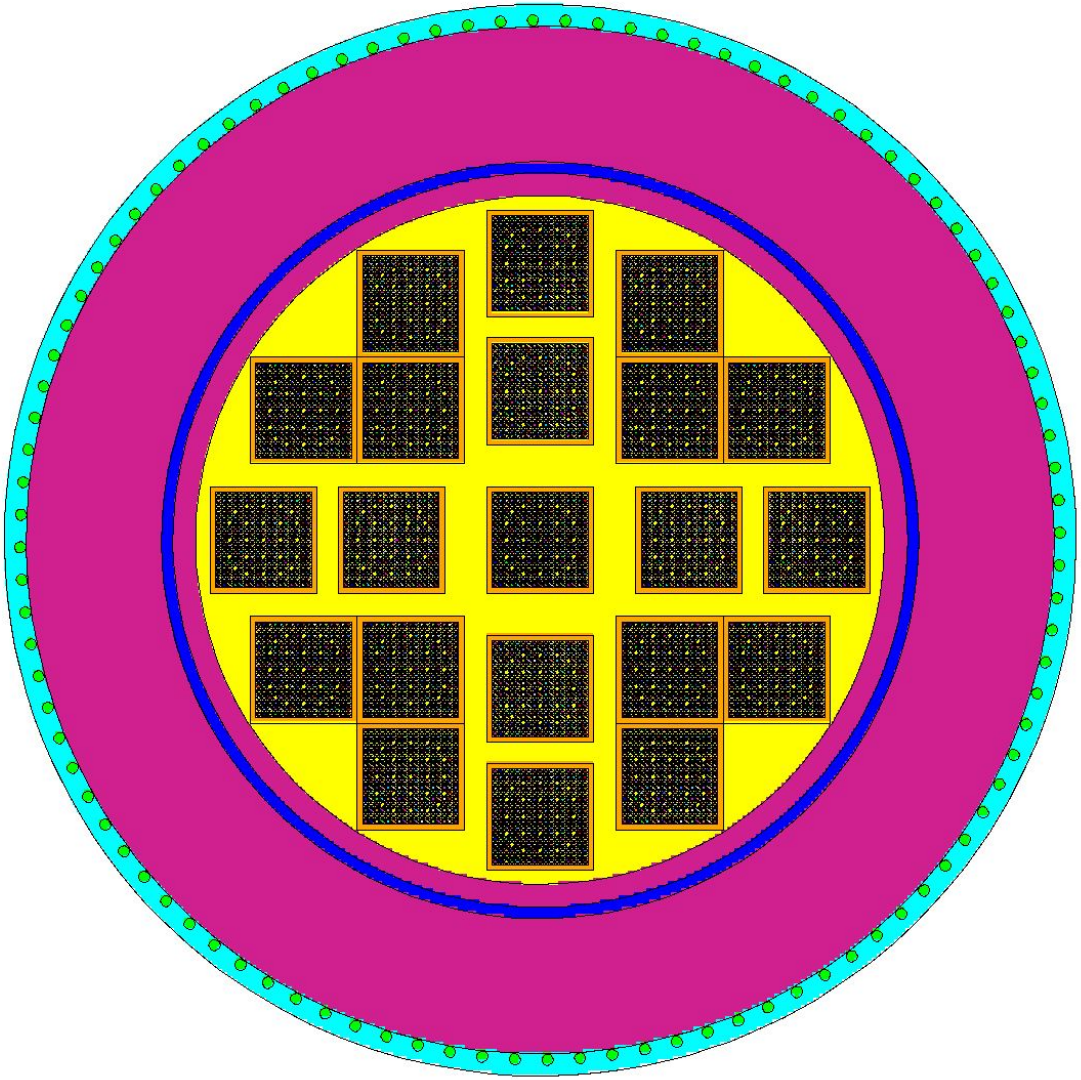
Acceptance Criteria

- **The ratios will oscillate around 1 due to stochastic and systematic effects as well as cask features**
- **2 Acceptance Criteria will be used to determine a match**
  – An FPV ratio matches if it falls within a specified range (0.87-1.13)
  – The number of FPV's that do not fall into that range must be less than 10% of the number of FPV's in the fingerprint
- **One criteria for acceptance of FPV ratios, one for the acceptance of a match**
- **These values are for the HI-STORM 100S with MPC-32 canister system**
  – Future studies could change these acceptance criteria
  – A simulation matrix for establishing the criteria still tentative

Description of Models

- Using Safety Analysis Reports from multiple cask designs, MCNP models of casks were created
- The Next Generation Safeguards Initiative had produced a library of simulated used fuel with varying burnup and cooling time
- Using the library to generate different loadings for multiple casks, the proposed signature could be tested
- The initial tests showed strong identification trends

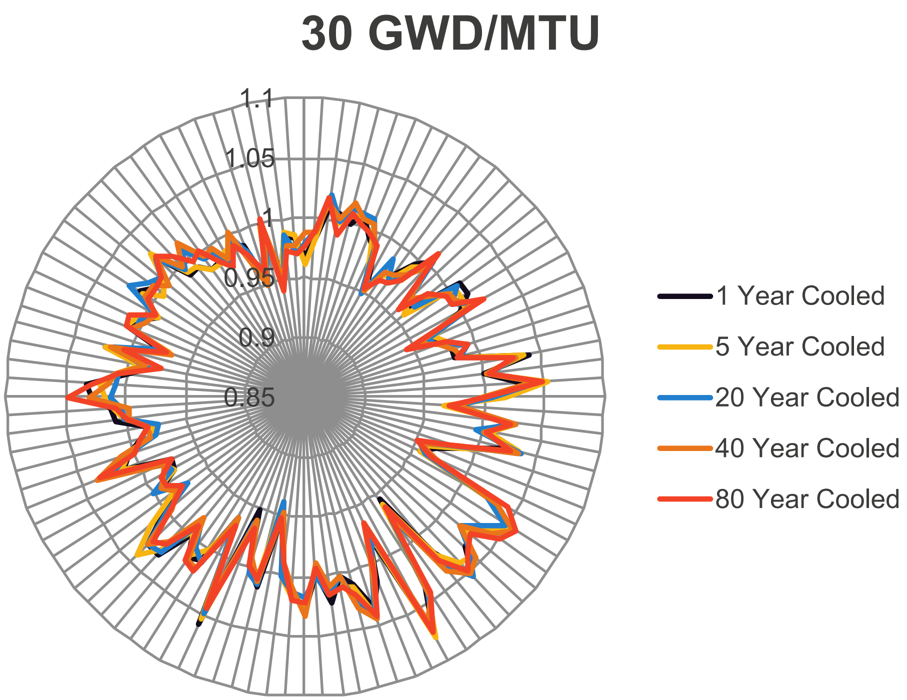
CASTOR V/21 Cask

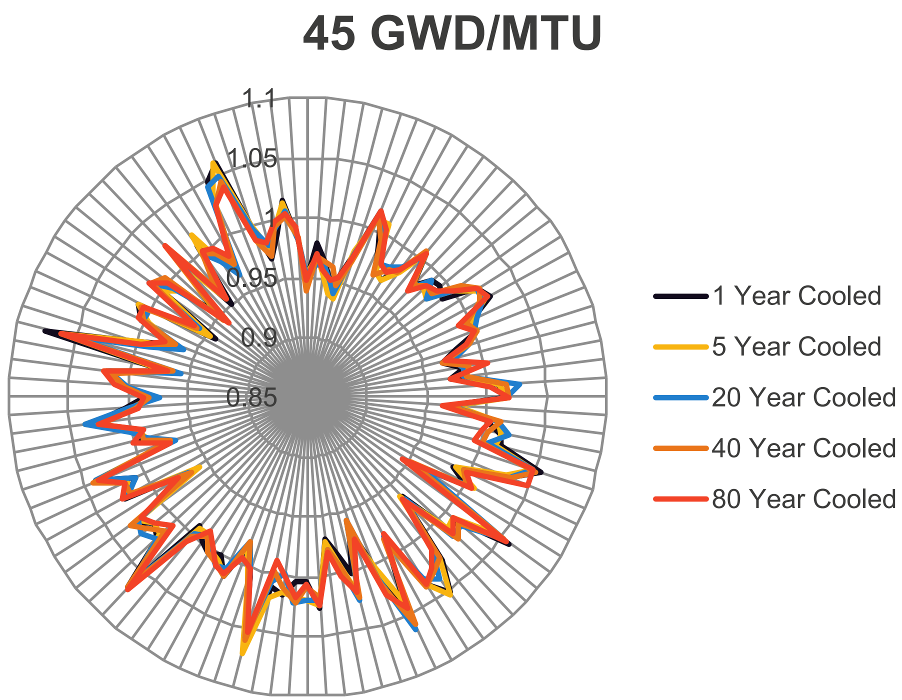


CASTOR V/21 Tests

- **Simple Cask Model**
  - Fuel
  - Steel
  - Poly
  - Steel
  - Air with detectors
- **Started with line sources an no fuel**
- **Added simulated used fuel from NGSI effort**

Signatures over time



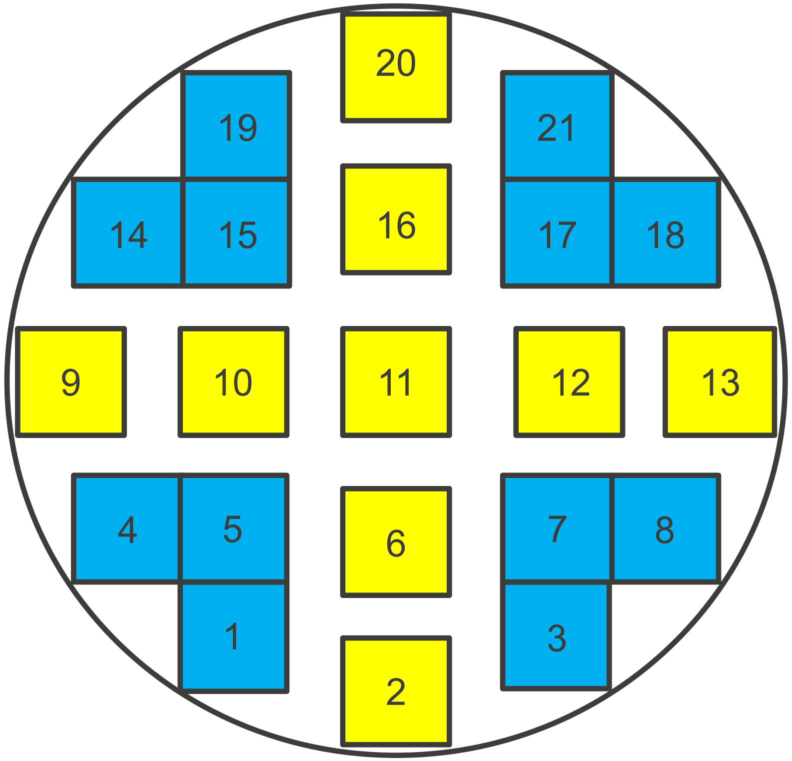


Signatures over time

	30 GWd 1 Year	30 GWd 5 Year	30 GWd 20 Year	30 GWd 40 Year	30 GWd 80 Year	45 GWd 1 Year	45 GWd 5 Year	45 GWd 20 Year	45 GWd 40 Year	45 GWd 80 Year
30 GWd 1 Year	Pass	Pass	Pass	Pass	Pass	Fail	Fail	Fail	Fail	Fail
30 GWd 5 Year	Pass	Pass	Pass	Pass	Pass	Fail	Fail	Fail	Fail	Fail
30 GWd 20 Year	Pass	Pass	Pass	Pass	Pass	Fail	Fail	Fail	Fail	Fail
30 GWd 40 Year	Pass	Pass	Pass	Pass	Pass	Fail	Fail	Fail	Fail	Fail
30 GWd 80 Year	Pass	Pass	Pass	Pass	Pass	Fail	Fail	Fail	Fail	Fail
45 GWd 1 Year	Fail	Fail	Fail	Fail	Fail	Pass	Pass	Pass	Pass	Pass
45 GWd 5 Year	Fail	Fail	Fail	Fail	Fail	Pass	Pass	Pass	Pass	Pass
45 GWd 20 Year	Fail	Fail	Fail	Fail	Fail	Pass	Pass	Pass	Pass	Pass
45 GWd 40 Year	Fail	Fail	Fail	Fail	Fail	Pass	Pass	Pass	Pass	Pass
45 GWd 80 Year	Fail	Fail	Fail	Fail	Fail	Pass	Pass	Pass	Pass	Pass

Mixed Burnup

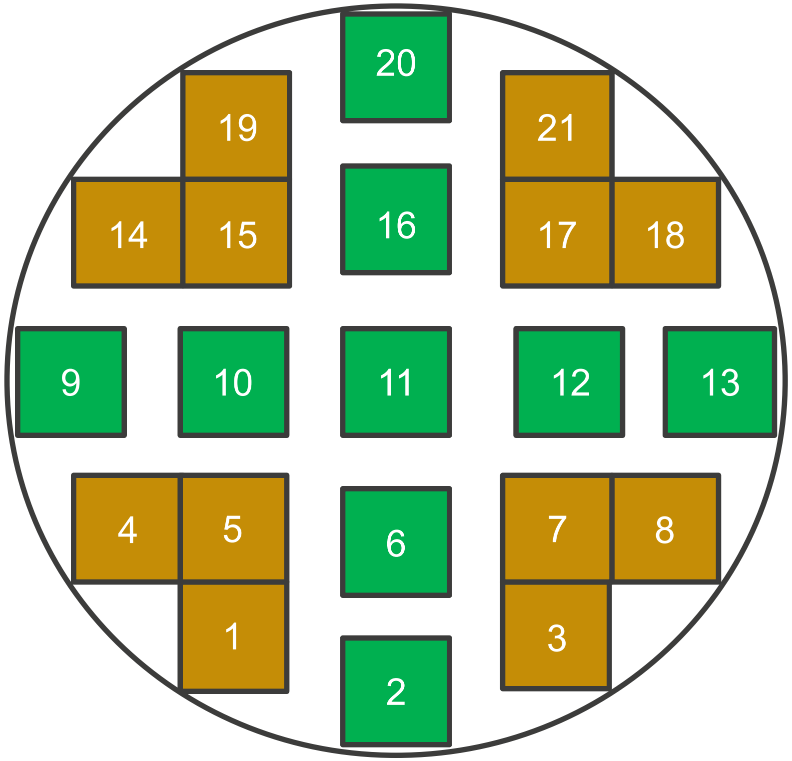
Years Cooled	1	5	20	40	80
1	X	Fail	Fail	Fail	Fail
5	Fail	X	Pass	Pass	Pass
20	Fail	Pass	X	Pass	Pass
40	Fail	Pass	Pass	X	Pass
80	Fail	Pass	Pass	Pass	X



Blue assemblies are 45 GWd, Yellow Assemblies are 30 GWd

Mixed Cooling Time

- 2 sets of simulations featuring either 30 GWd or 45 GWd fuel
- Each burnup had simulations with 1 and 40 years cooled as well as 40 and 80 years cooled
- Fingerprints from similar casks matched

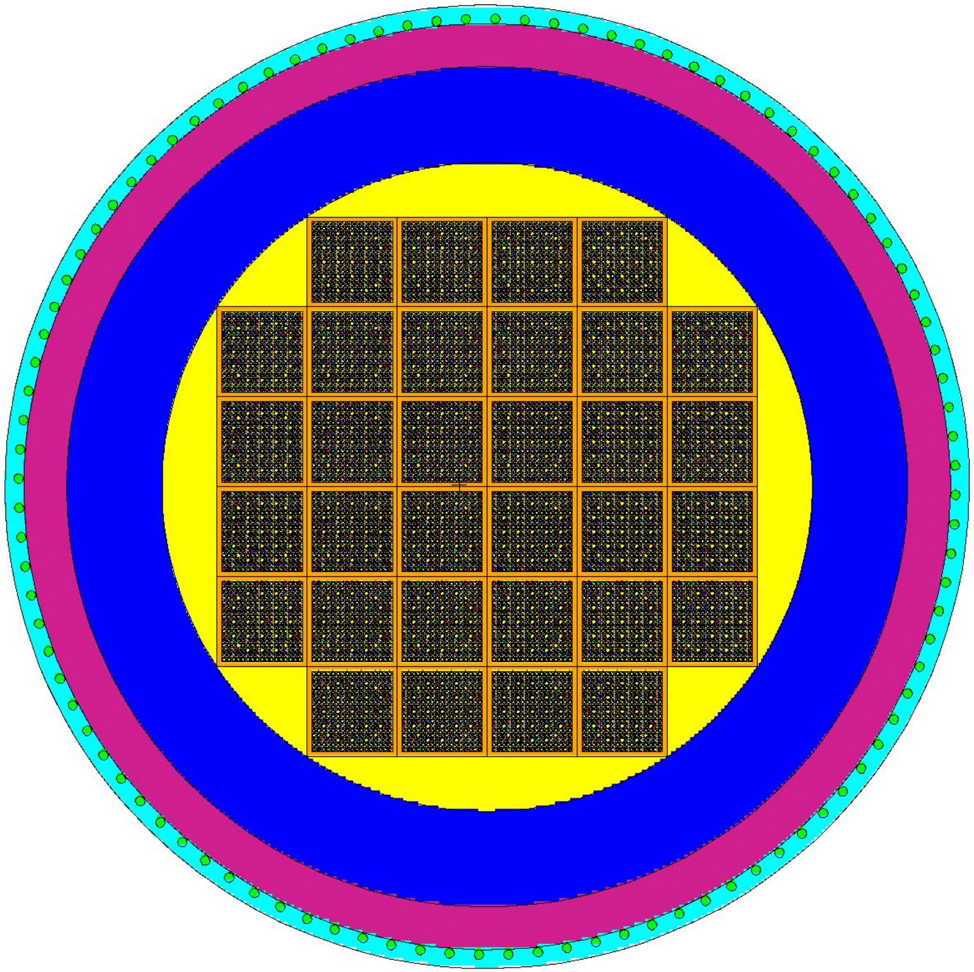


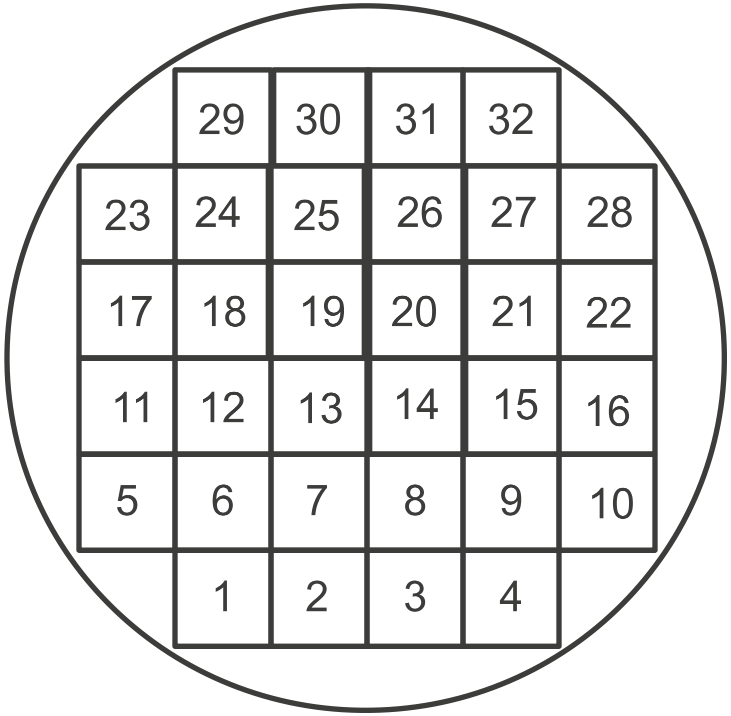
2 simulations per burnup, younger fuel in gold, older fuel in green

CASTOR Conclusions

- Proposed method works for mixed burnup/cooling time and provides unique signatures for each specific loading
- Cask model very simple, did not include burnable poisons or all of the cask structure
- Need higher fidelity model and more fuel assemblies in a different geometry

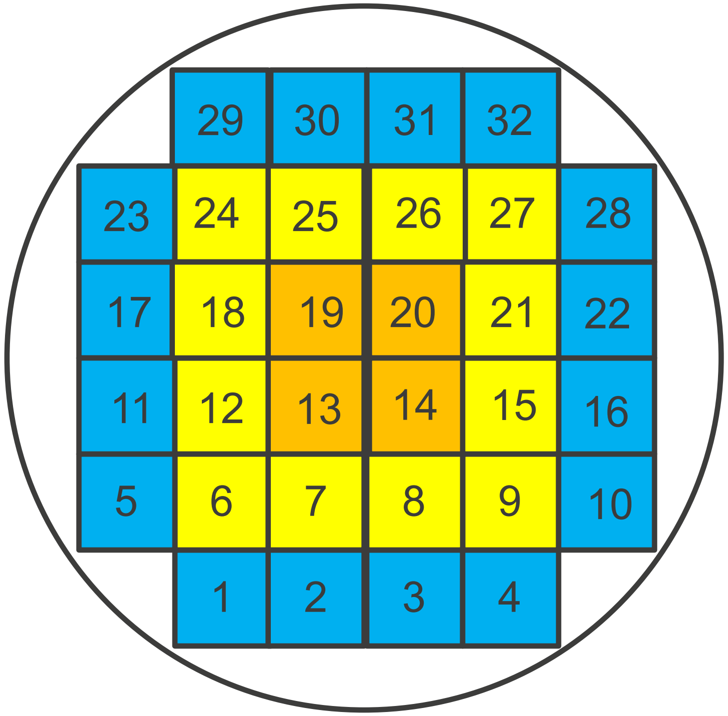
TN-32 Model




29 30 31 32
23 24 25 26 27 28
17 18 19 20 21 22
11 12 13 14 15 16
5 6 7 8 9 10
1 2 3 4

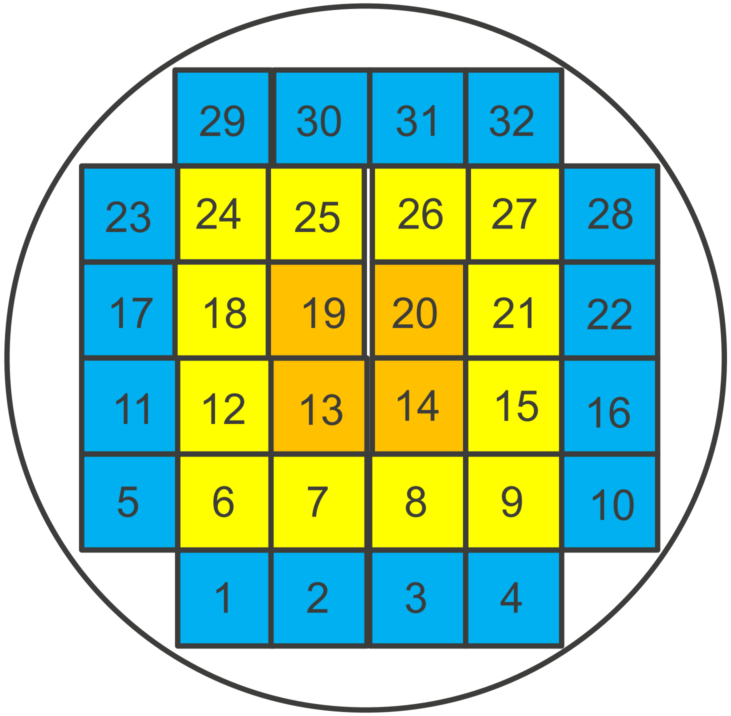
Matched Sets Comparison

- 3 different assemblies and 2 points in time
- Compares 2 arrangements of burnup distribution over 20 years
- Each simulation is constructed twice, with 20 years more cooled fuel in the second set



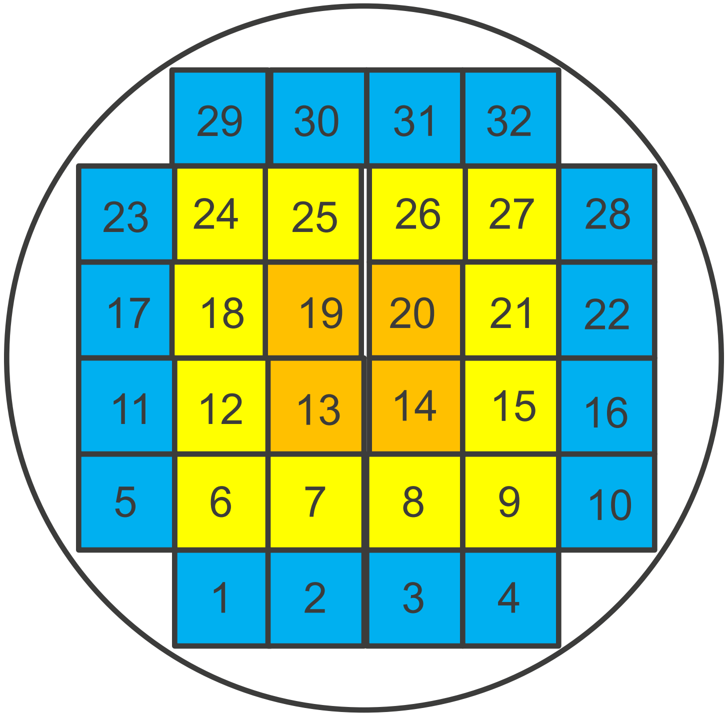
Each color represents a different burnup/cooling time

Set 1



Blue – 45 GWd and 1 and 20 years
Yellow – 45 GWd and 20 and 40 years
Orange – 30 GWd and 20 and 40 years

Set 2



Blue – 45 GWd and 1 and 20 years
Yellow – 30 GWd and 1 and 20 years
Orange – 30 GWd and 20 and 40 years

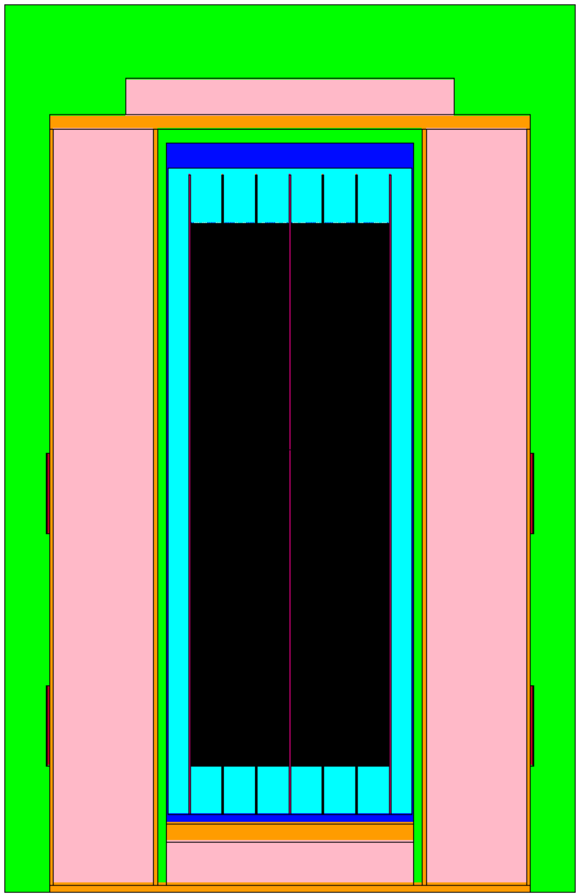
Method Succeeds!

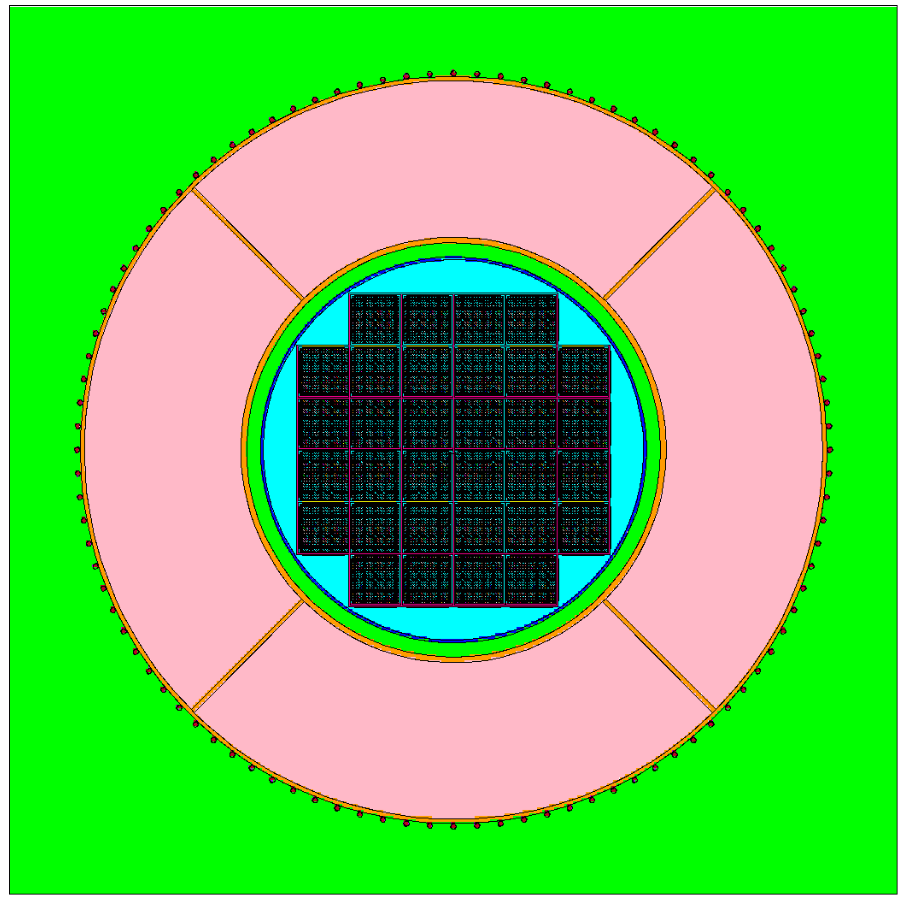
	Set 1	Set 1 + 20 Years	Set 2	Set 2 + 20 Years
Set 1	Pass	Pass	Fail	Fail
Set 1 + 20 Years	Pass	Pass	Fail	Fail
Set 2	Fail	Fail	Pass	Pass
Set 2 + 20 Years	Fail	Fail	Pass	Pass

TN-32 Results

- Higher fidelity added complexity, did not stop identification method from correctly identifying casks in most cases
- Some tests did start to show limits of the method
- Enough evidence to create most realistic model yet

HI-STORM 100S with MPC-32 Canister



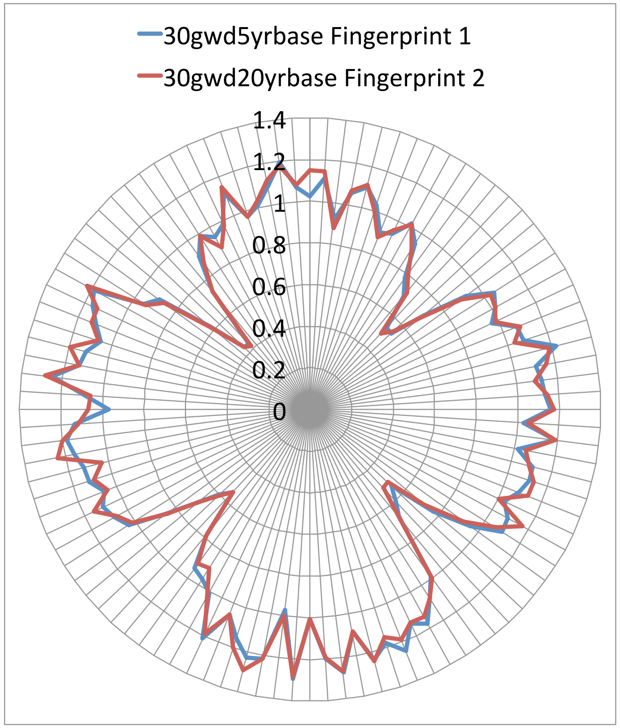


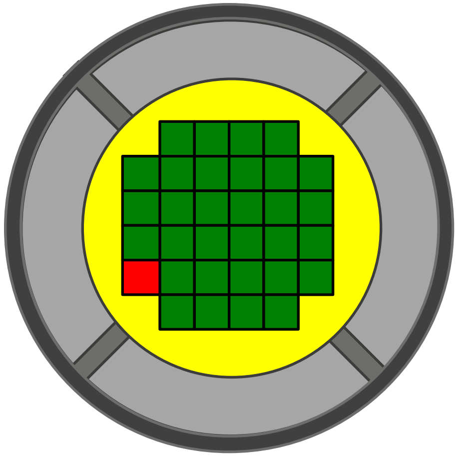
HI-STORM 100S with MPC-32 Canister

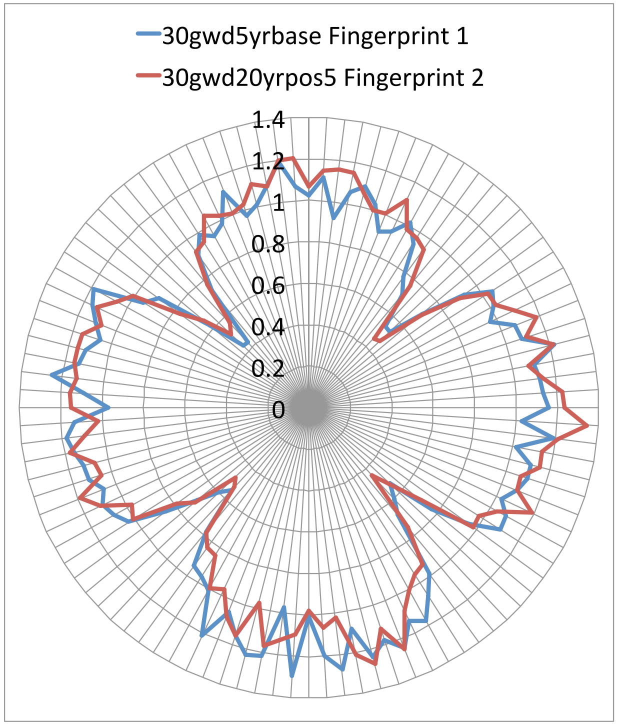
- **Highest fidelity model**
- **Most common style of cask**
  - Canister system with overpack
  - Same overpack can accept variety of canisters
  - Same canister can be used in different overpacks
- **MPC-32**
  - Steel fuel basket
  - Neutron absorbing plates with fuel
  - Sealed prior to placement in overpack
- **HI-STORM 100S**
  - Steel and Concrete
  - Open to environment
  - Iron Structural pieces impact neutron leakage

2 Comparisons, on left a full cask aged 15 years, on right a cask with one assembly removed from position 5 after aging for 15 years

Acceptance Criteria must be set to match the fingerprints on the left, but not match the fingerprints on the right

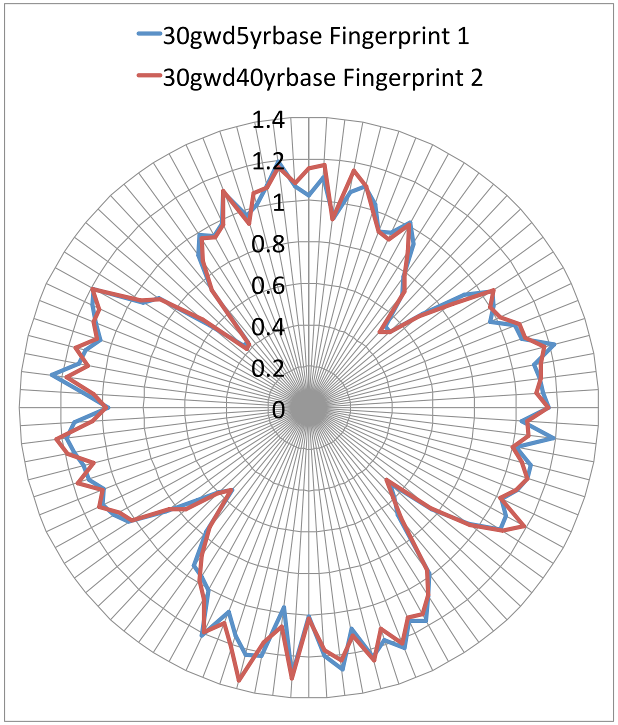


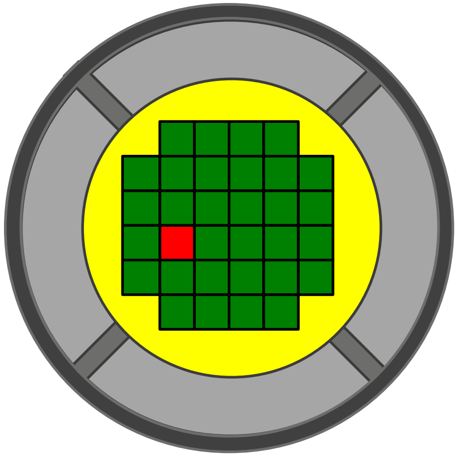


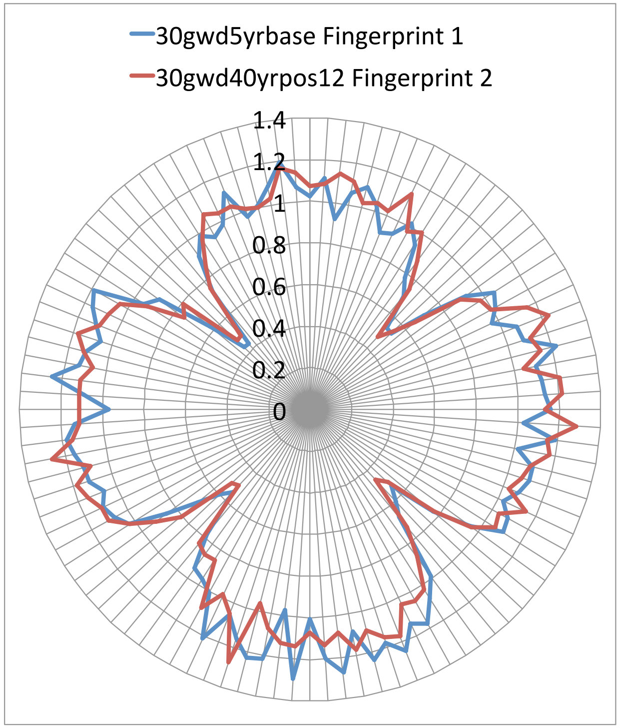


2 Comparisons, on left a full cask aged 35 years, on right a cask with one assembly removed from position 12 after aging for 35 years

Comparison between 35 years aging and 15 years aging shows little difference in fingerprint shape or matching

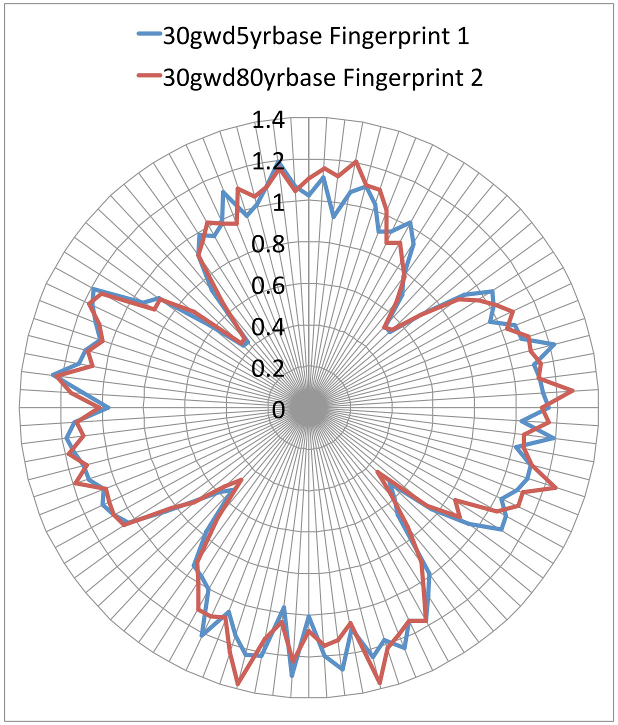


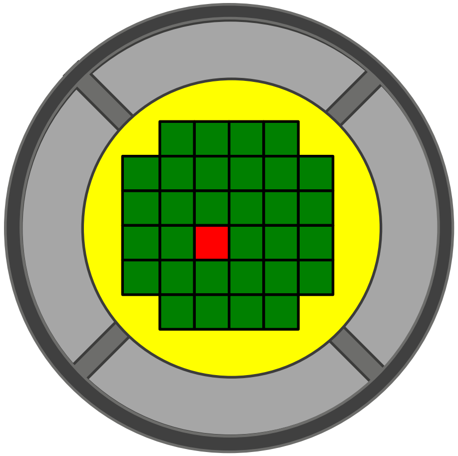


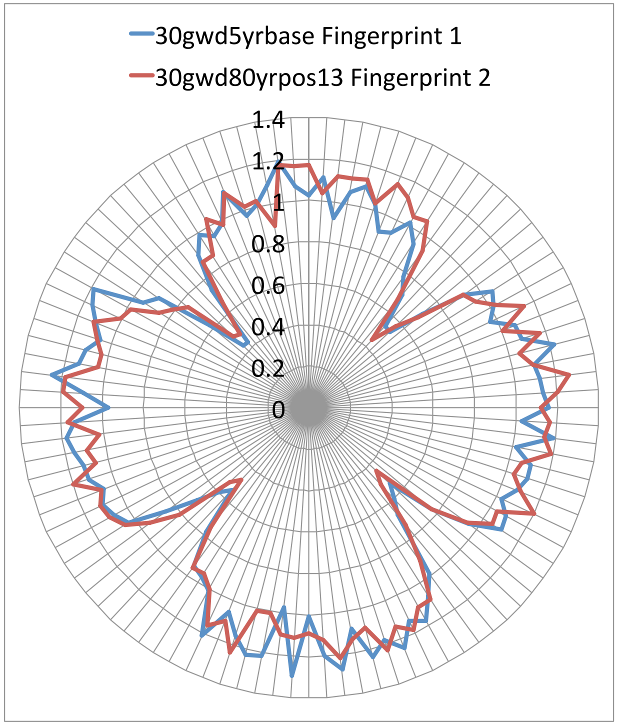


2 Comparisons, on left a full cask aged 75 years, on right a cask with one assembly removed from position 13 after aging for 75 years

Comparison on left starting to appear more like the one on the right, compared to previous slides







Results from first round of tests

- Differences between decayed models and non decayed models showing fewer differences with this model
- Harder to determine if central assemblies can be seen if removed
- Need more fidelity in used fuel models

Real data from 3 actual MPC-32 Cannisters

- Data provided by ORNL
- Neutron emission rates and spectrum with axial profile for 96 assemblies
- Loading pattern provided
- Using simulated spent fuel library for materials and source information from provided data, 3 simulations were created

Loading 1

	29 R68 1.229E+08	30 R60 1.255E+08	31 R49 1.273E+08	32 R51 1.280E+08	
23 R66 1.226E+08	24 D60 1.484E+08	25 T10 1.498E+08	26 T12 1.508E+08	27 D05 1.501E+08	28 D17 2.009E+08
17 D27 1.561E+08	18 T09 1.492E+08	19 T11 1.500E+08	20 S45 1.266E+08	21 S67 1.274E+08	22 D01 1.510E+08
11 D53 1.561E+08	12 S75 1.286E+08	13 R43 1.546E+08	14 F56 1.484E+08	15 F18 1.298E+08	16 D29 1.569E+08
5 D55 1.548E+08	6 D31 1.593E+08	7 F01 1.298E+08	8 R64 1.227E+08	9 D18 1.604E+08	10 D11 1.560E+08
	1 D24 1.569E+08	2 D52 1.614E+08	3 D36 1.667E+08	4 D40 1.691E+08	

Top number is position, Middle value is Assembly Name, Bottom value is neutron emission rate from assembly

- **Max – 2.009e08 n/s**
- **Min – 1.226e08 n/s**
- **Average – 1.468e08 n/s**
- **Total – 4.698e09 n/s**

Loading 2

	29 F35 1.361E+08	30 F60 1.372E+08	31 F37 1.394E+08	32 F63 1.356E+08	
23 F26 1.070E+08	24 F32 1.073E+08	25 J44 7.303E+07	26 J53 7.153E+07	27 F05 1.080E+08	28 P05 1.006E+08
17 S77 1.126E+08	18 J15 7.175E+07	19 J09 7.328E+07	20 J41 7.337E+07	21 J17 7.465E+07	22 S76 1.141E+08
11 E28 1.266E+08	12 J23 7.170E+07	13 D15 1.247E+08	14 D66 1.643E+08	15 G05 1.129E+08	16 E03 1.312E+08
5 E12 1.336E+08	6 F08 1.619E+08	7 G14 1.132E+08	8 G09 1.131E+08	9 F22 1.620E+08	10 F27 1.639E+08
	1 F33 1.441E+08	2 P21 8.974E+07	3 D47 1.993E+08	4 F68 1.472E+08	

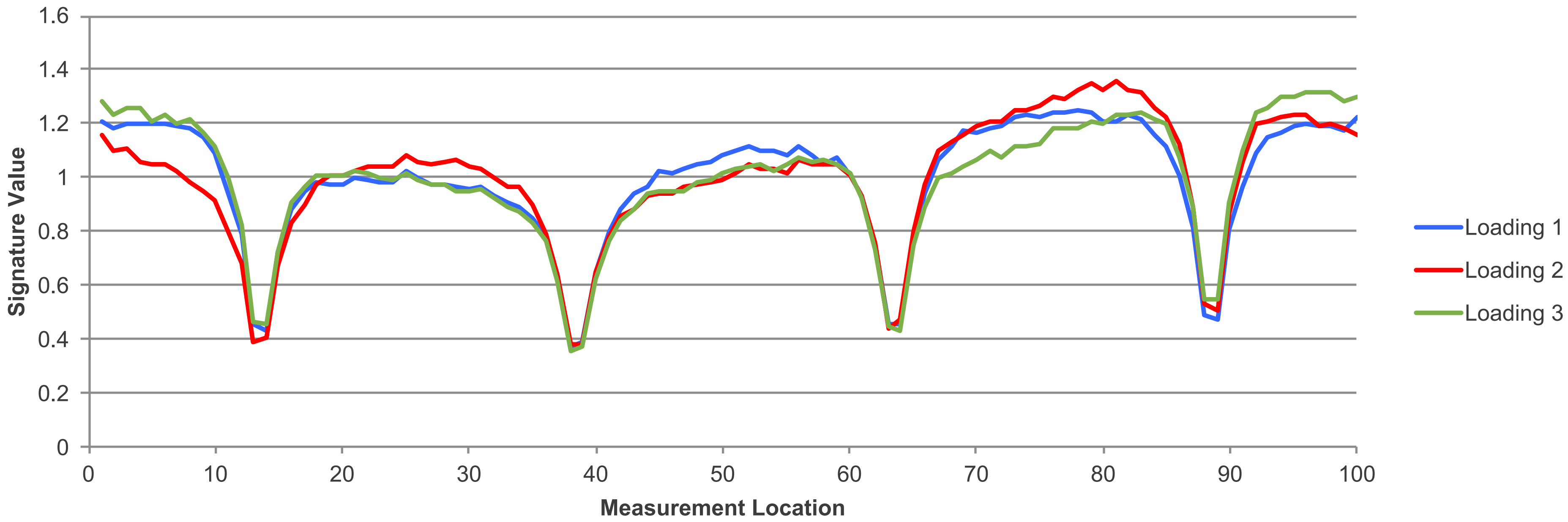
- Max – 1.993e08 n/s
- Min – 7.153e07 n/s
- Average – 1.186e08 n/s
- Total – 3.795e09 n/s

Loading 3

	29 R41 1.216E+08	30 R55 1.234E+08	31 R53 1.215E+08	32 R50 1.219E+08	
23 R52 1.232E+08	24 R67 1.213E+08	25 D38 1.568E+08	26 R44 1.566E+08	27 P29 1.972E+08	28 P11 1.961E+08
17 P63 1.156E+08	18 E01 1.635E+08	19 F23 1.572E+08	20 F13 1.582E+08	21 E52 1.674E+08	22 R46 1.195E+08
11 R48 1.207E+08	12 F11 1.603E+08	13 F25 1.653E+08	14 E02 1.772E+08	15 R42 1.213E+08	16 D28 1.861E+08
5 D32 1.904E+08	6 D67 1.833E+08	7 R57 1.225E+08	8 R56 1.228E+08	9 D07 1.967E+08	10 D37 1.951E+08
	1 N45 1.126E+08	2 N32 1.162E+08	3 N47 1.537E+08	4 M39 1.870E+08	

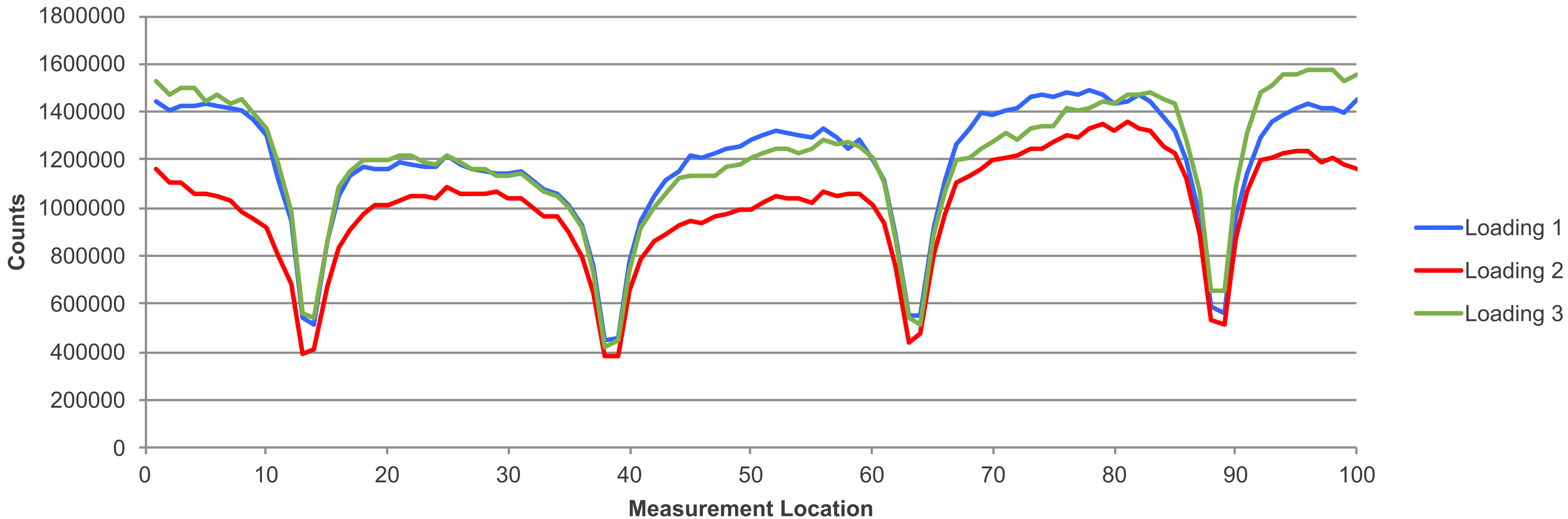
- **Max – 1.972e08 n/s**
- **Min – 1.126e08 n/s**
- **Average – 1.510e08 n/s**
- **Total – 4.832e09**

Initial Results



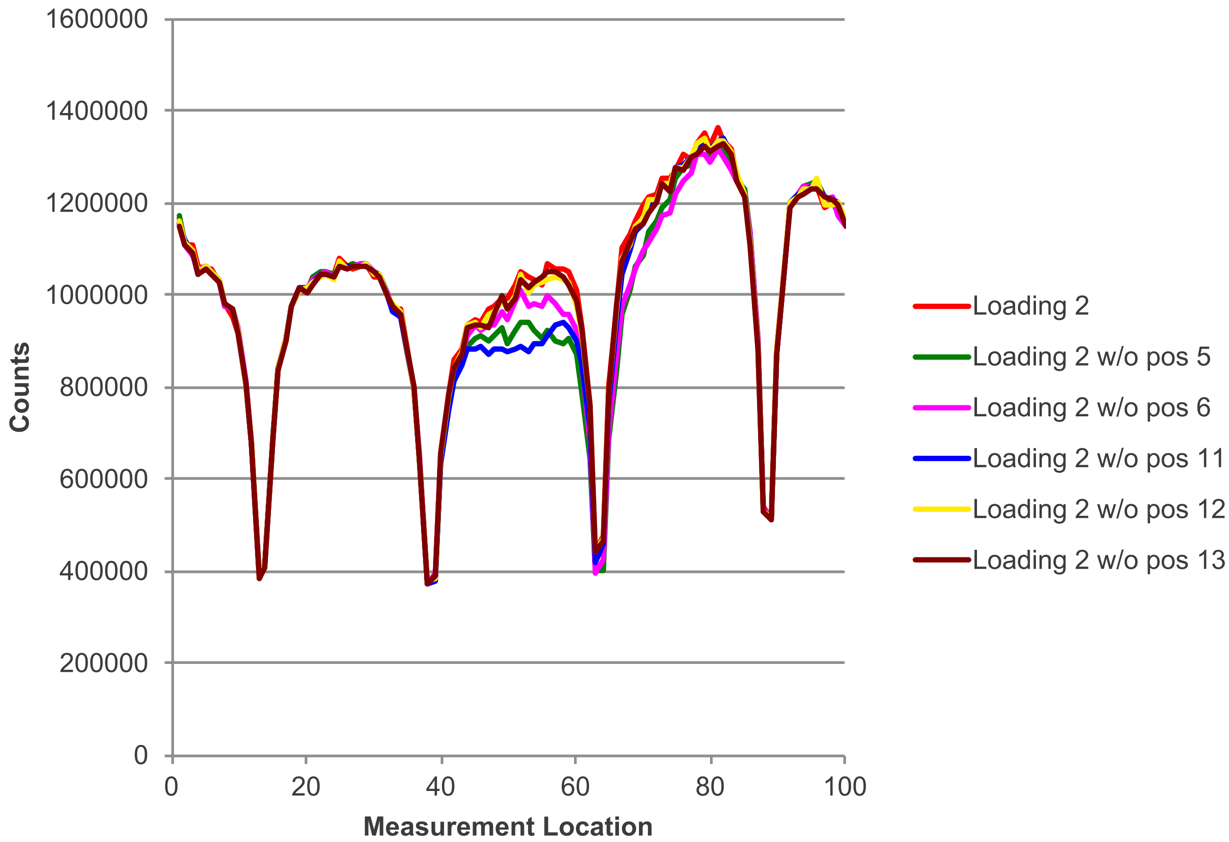
Visible differences in the profile are evident. If more than 5 SV are greater than 5% different in comparison to another measurement, no match.

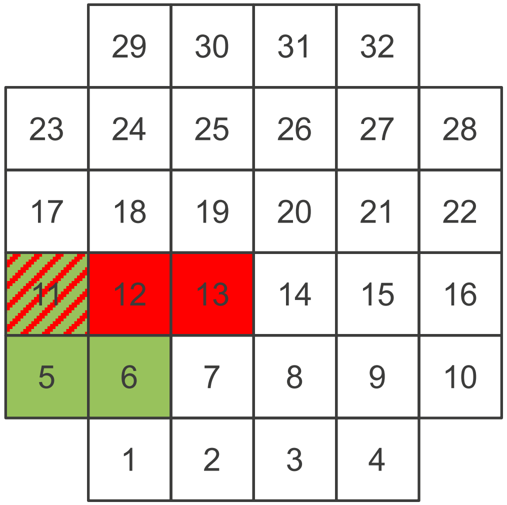
Simulated Measurement Results



Loading 2 produces significantly lower measurements. Lower measurements expected due to older fuel, with lower neutron emission rates.

Removal of an Assembly





Findings

- Identification of cask loadings works well through the profile of emitted neutrons in simulated real casks
- Even casks with similar overall neutron emission or average counts around the circumference can be distinguished from each other by analyzing the profile
- Collecting profile provides other potentially useful information
- Signature is less reliant on multiplication than previous studies indicated
- There is a significant change in counts with removal of assemblies
- Looking at percent decrease over time per detector could still offer insight on state of fuel inside cask

Final Thoughts

- Neutron leakage profile provides information on the state of the fuel inside a cask
- More work needed to find what the limits really are
- Testing on real casks is the next step
- Current effort underway here is promising, will be interested in how it continues going forward
- Safeguards for casks is still not well thought out or planned, more work in this area is needed

Thanks!

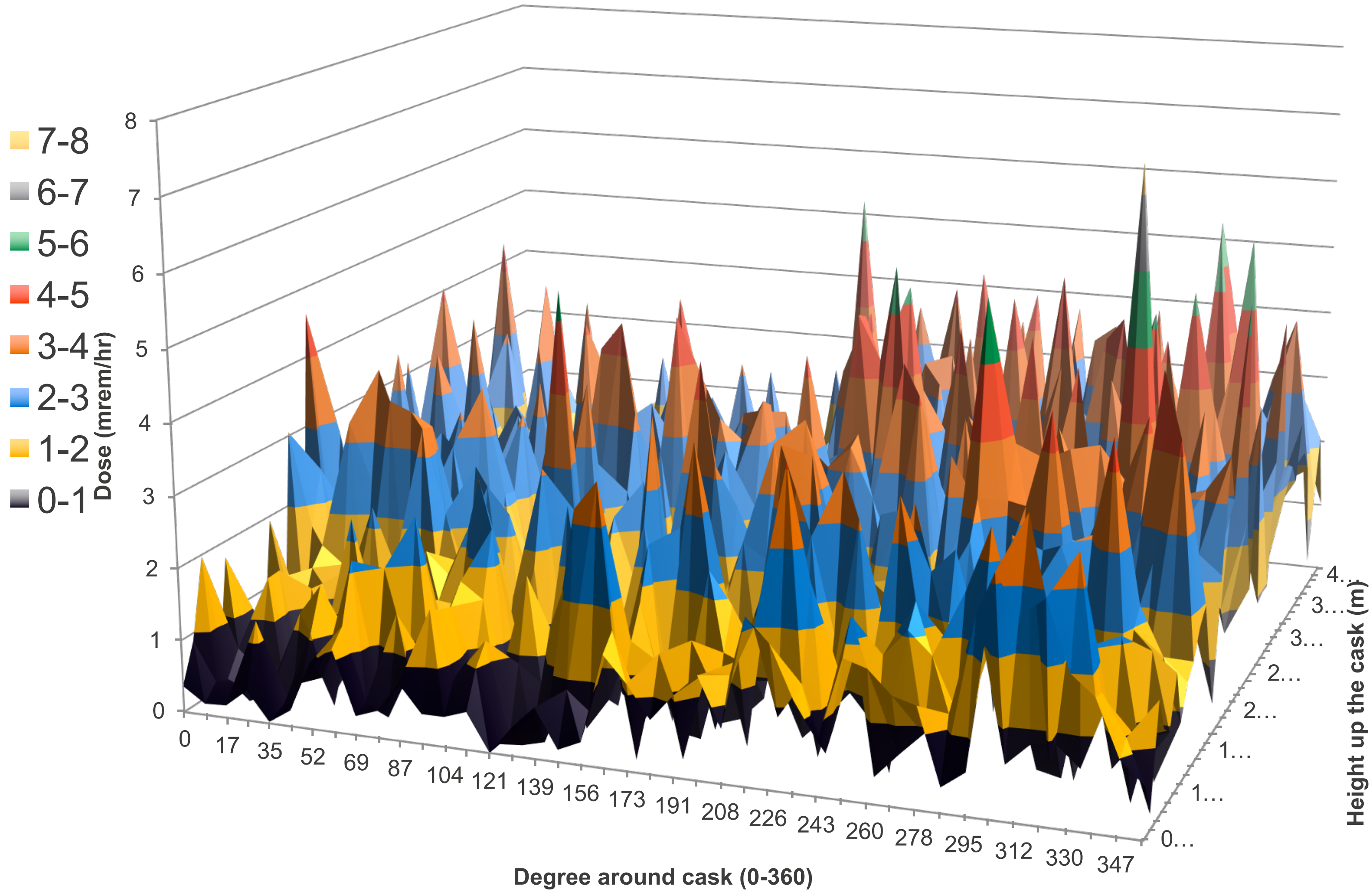
Benchmarking Data Review

- Several previous measurement campaigns have been completed on used fuel casks
- Used Fuel Cask Demonstration located at INL well suited for some testing
- In 2003, a small measurement campaign was completed
- Using a E-600 Survey Meter with neutron REM detector (E-600/NRD), or REMBall, a series of 20 second measurements were made around a VSC-17 cask
- This cask is a downsized version of the commercially available VSC-24 cask
- It contains the fuel from ~20 assemblies, as some assemblies had been de-constituted and the pins from these assemblies stored with other assemblies in the fuel basket.

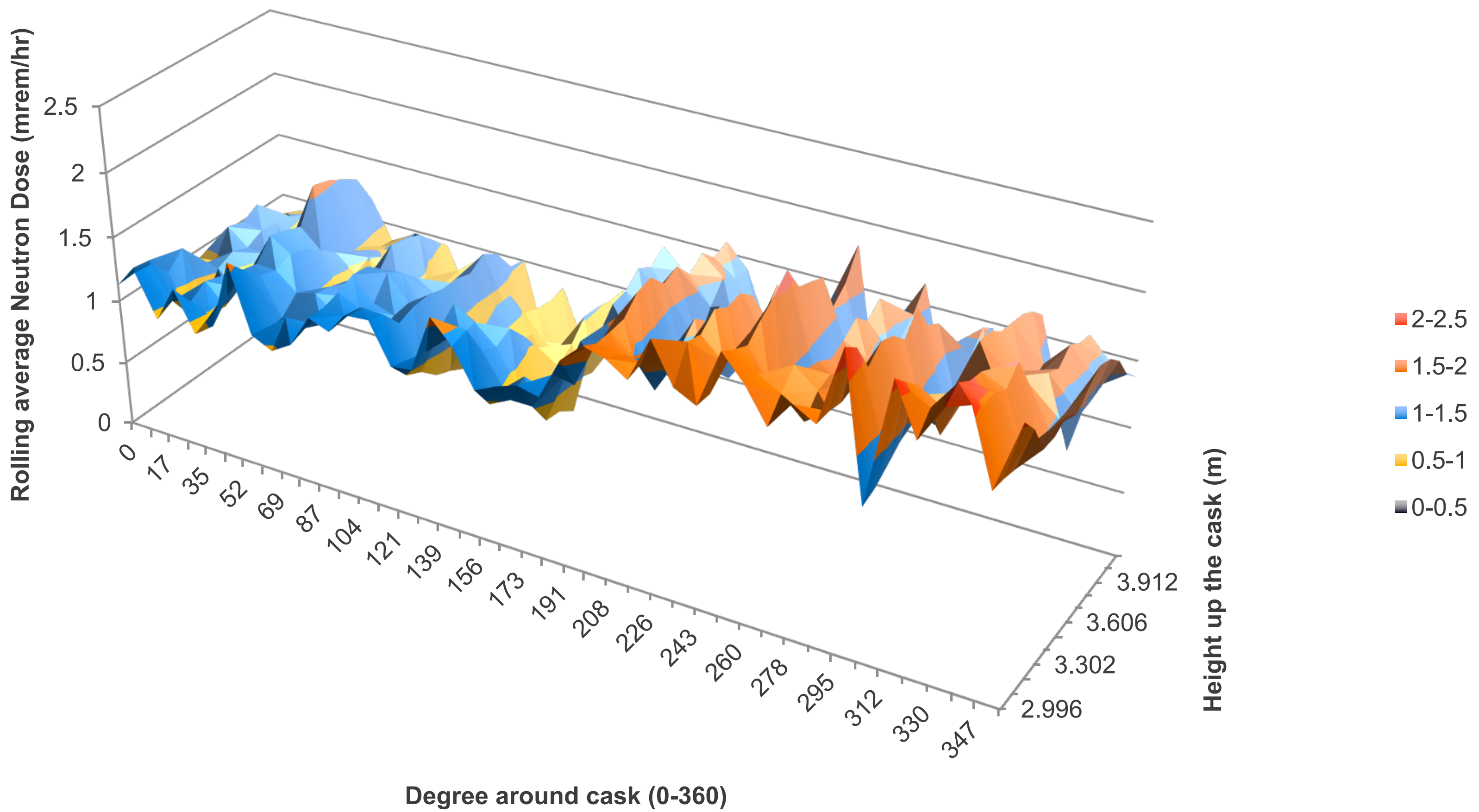

LOWEST
TOTAL
VERTICAL


SLA-20

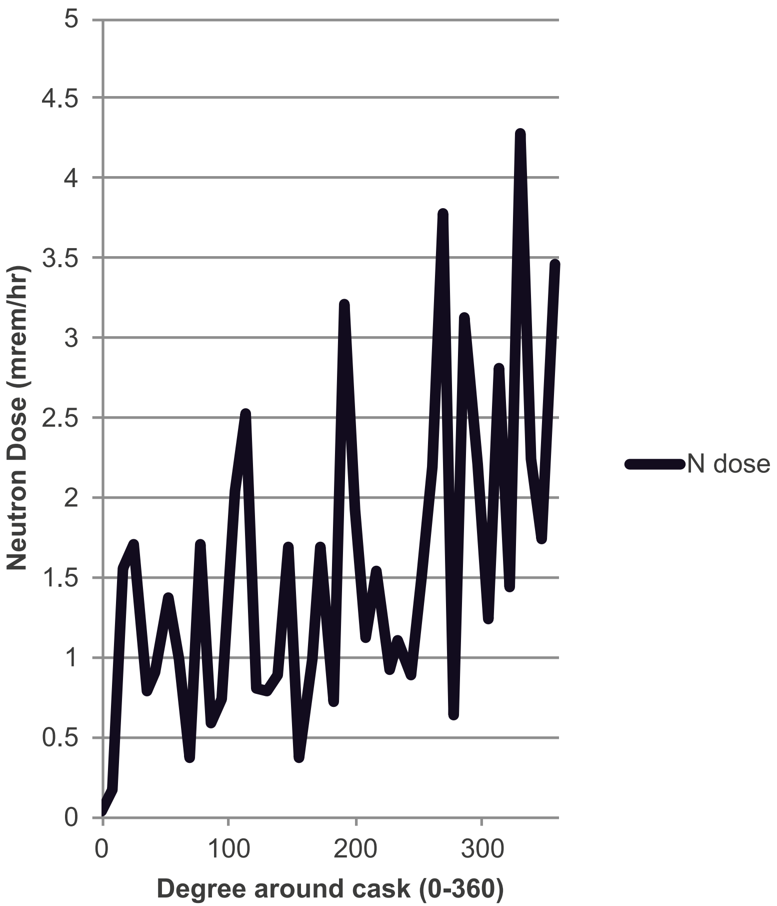
Raw Benchmarking data

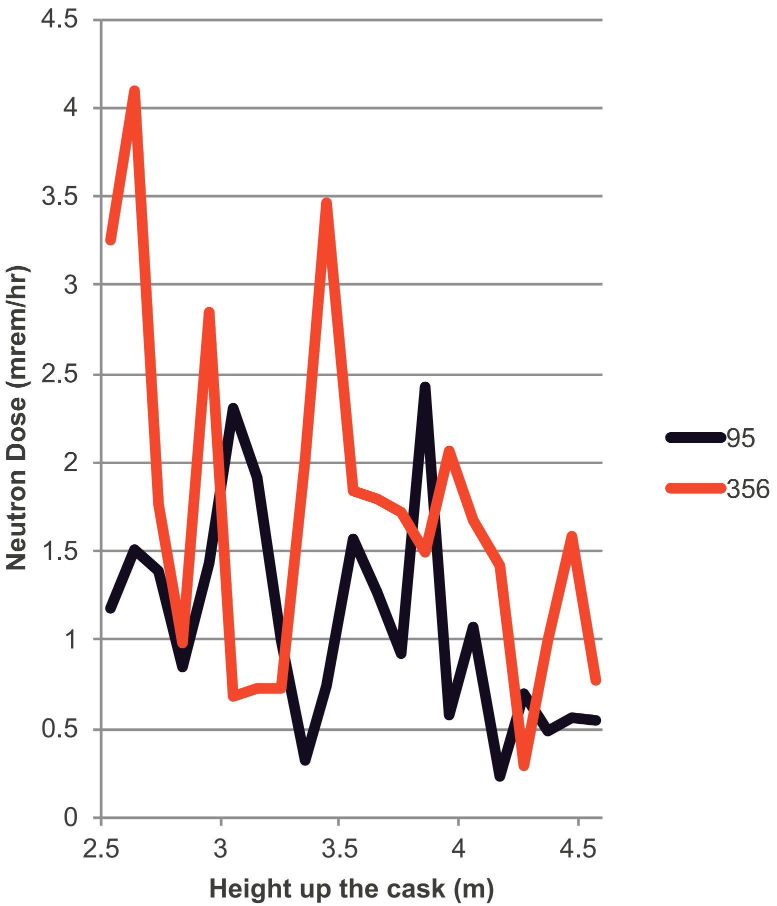


Rolling 10 measurement average, top half of the cask



Vertical and Horizontal Slices





Analysis of Benchmark Data

- Not enough data to definitively test proposed identification method
- General trends provide some indications that neutron emission is not uniform around the cask
- Longer count times, with a more efficient detector is needed